Progress on the Pulsed Fission-Fusion Propulsion System Concept

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PuFF Concept

Introduction to PuFF

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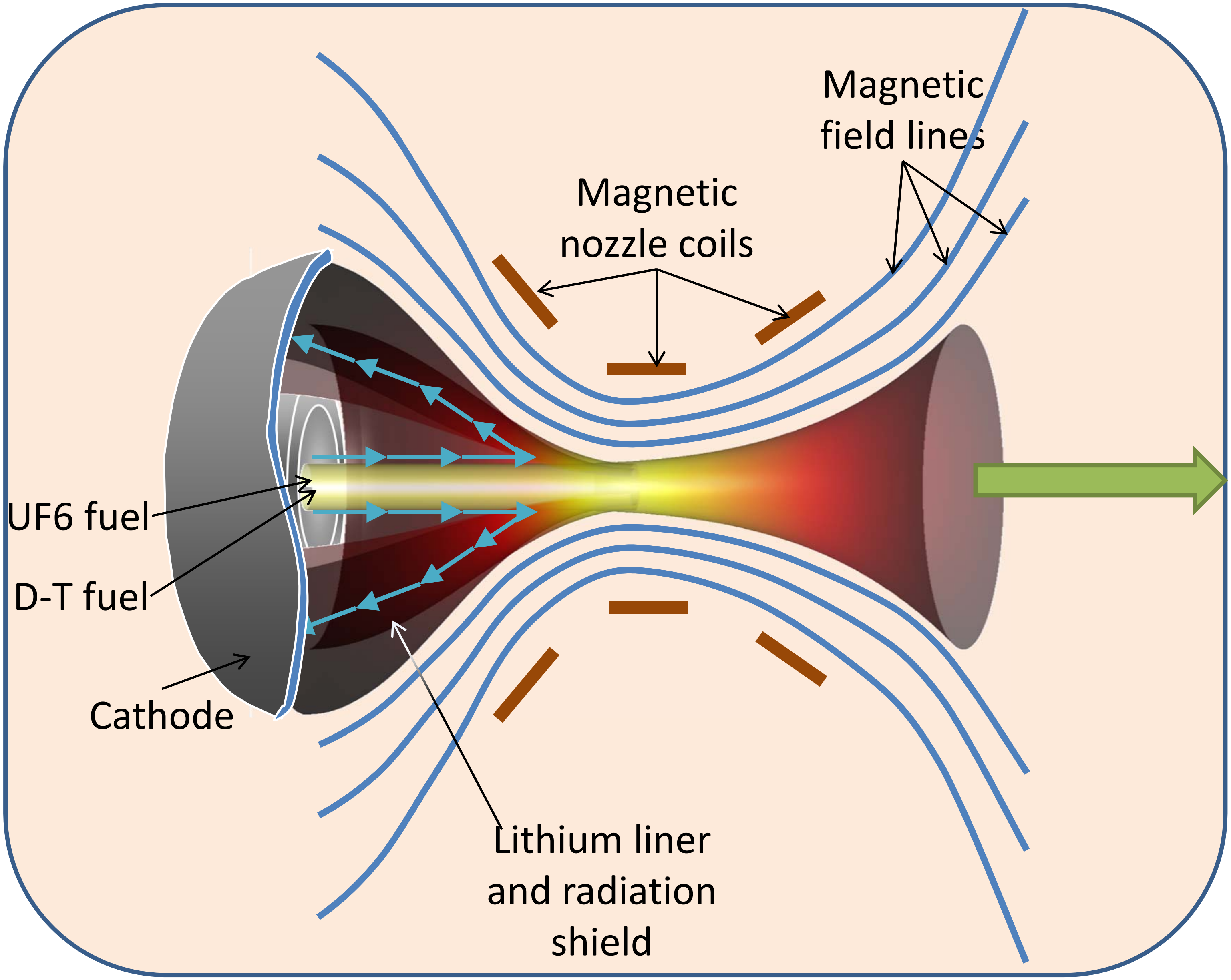
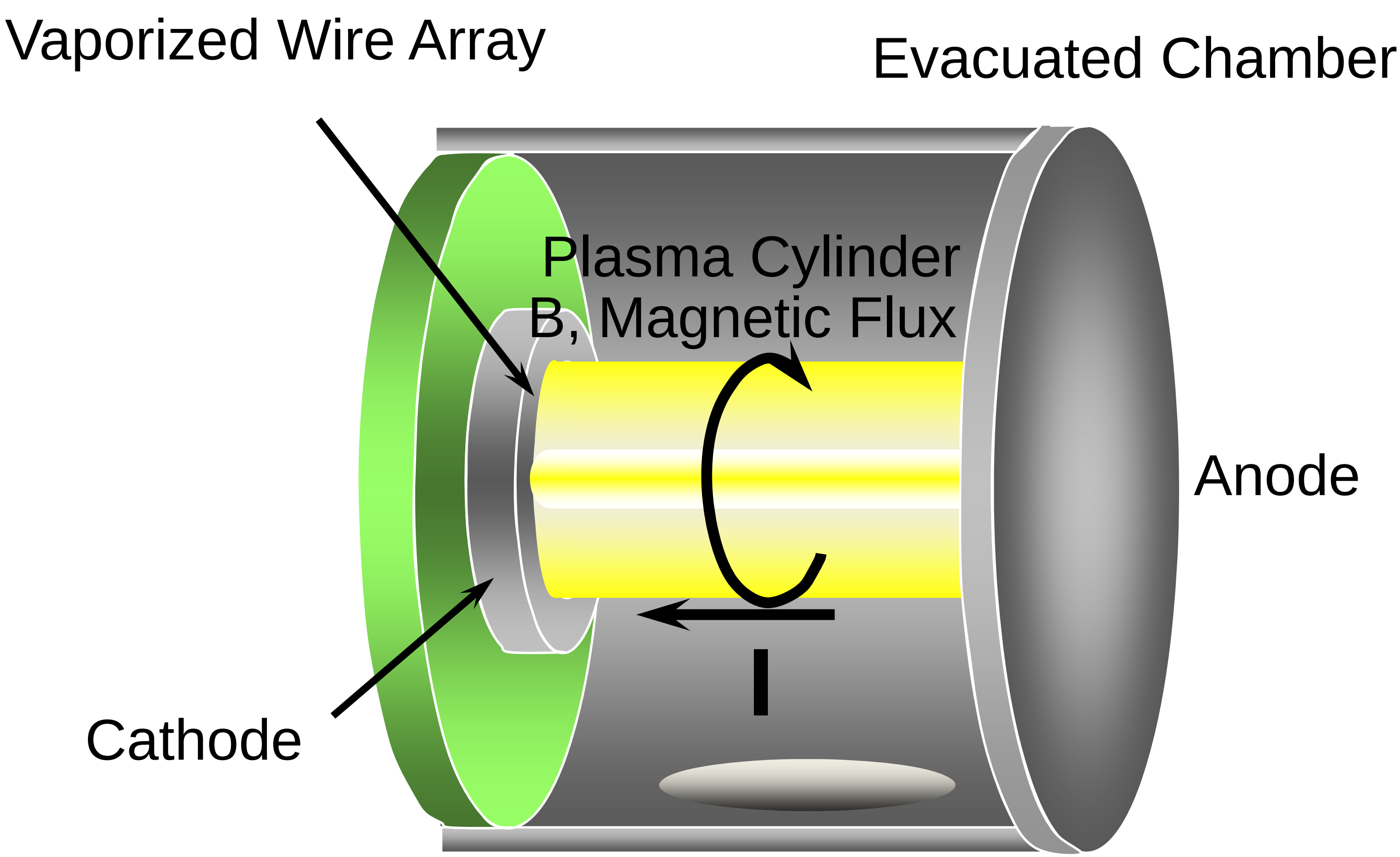
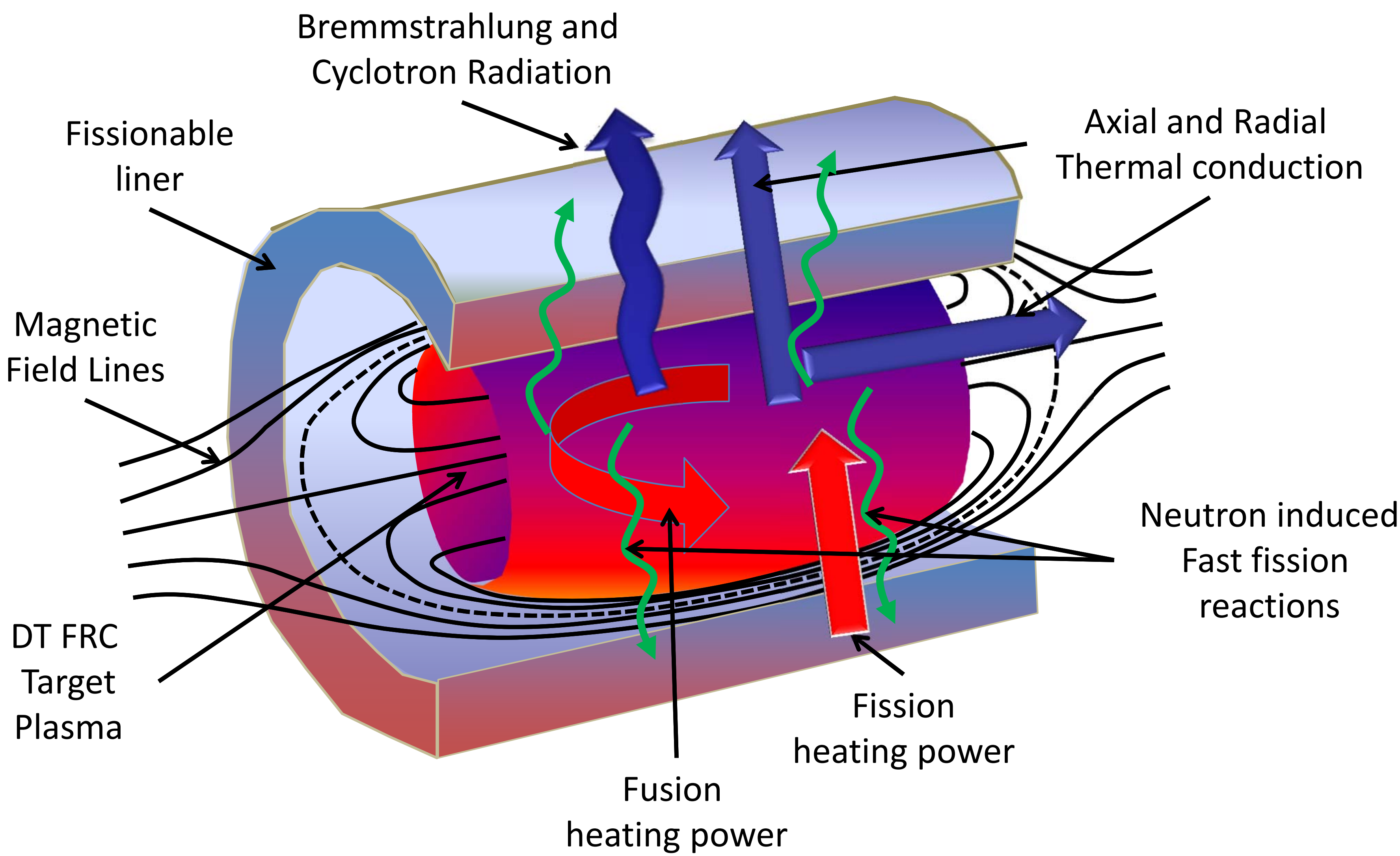


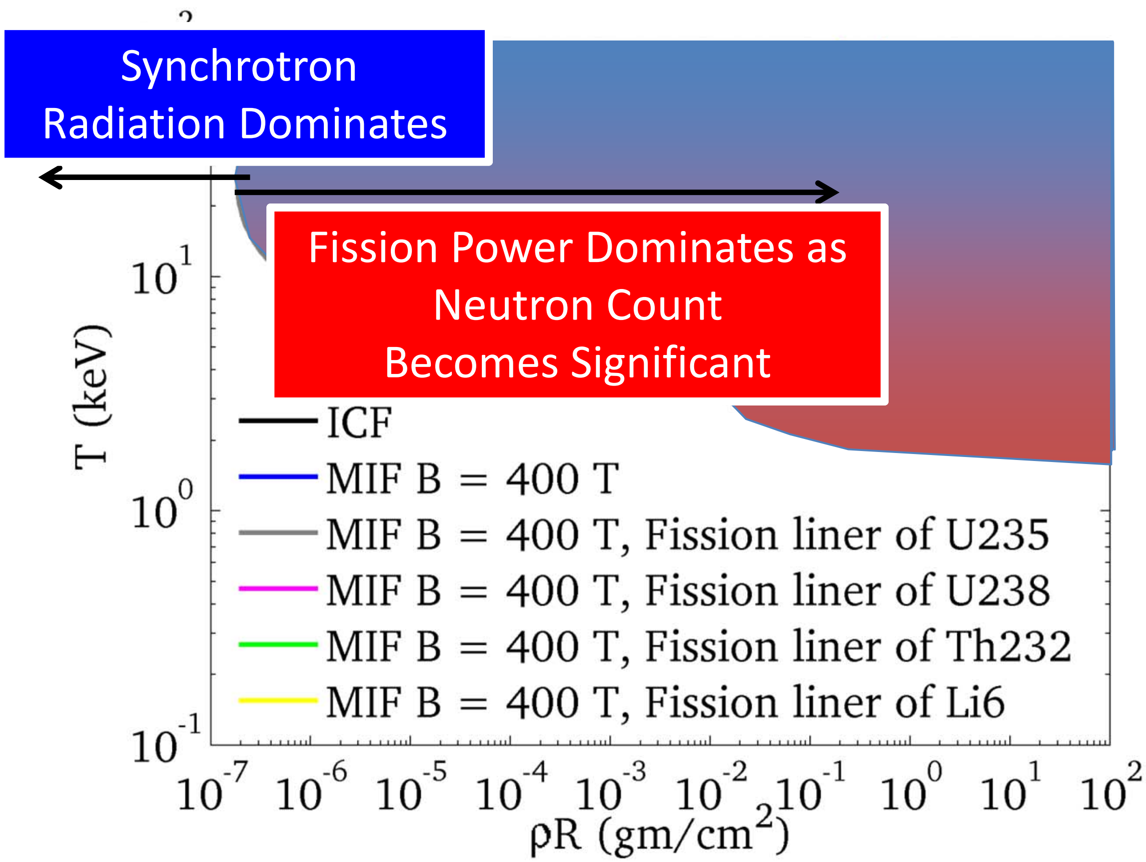
Operation of a Z Pinch



Heating Mechanisms Included in Model



Fusion Power Balance



- Parameter space for ignition
- Greatly broadened with embedded magnetic field
- Marginally improved with ^{6}Li and thorium liners
- Significantly enhanced with uranium liners (^{235}U and ^{238}U)

Parameters within net Power Increase

- Choose ρ R = 10^{-5} at 15 keV.
- Let R = 1 mm, thickness of uranium liner is 5 mm, length of target is 2 cm
- Density of DT target is 0.1 kg/m^3
- Total energy in DT target is only ~5 kJ, 1% of Charger 1 stored energy

Our Approach: Solve Maxwell's Equations Coupled to Multifluid (Ions, Electrons, Neutrals) Equations of Motion

Maxwell's Equations

- Solve with Smooth Particle Electromagnetic Variant of Finite-Difference Time Domain (FDTD) method
- FDTD well documented, highly accurate grid-based method for analyzing the time evolution of electric and magnetic fields, utilized in PIC codes
- Can interpolate charged fluid particles to grid to model conductivity or charge and current density

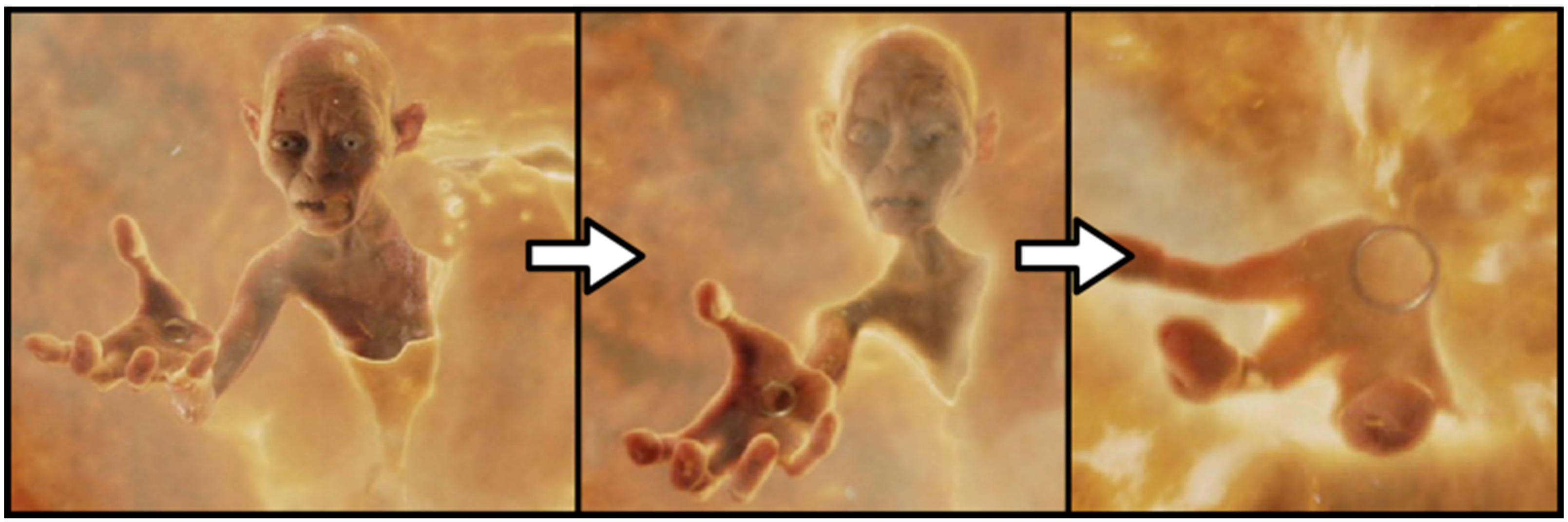
Multifluid Equations of Motions

- Solve with Smooth Particle Hydrodynamics (SPH)
- Gridless Lagrangian technique
- <u>Vacuum/plasma boundary well defined</u>
- Leverage same engine as Maxwell Equation Solver

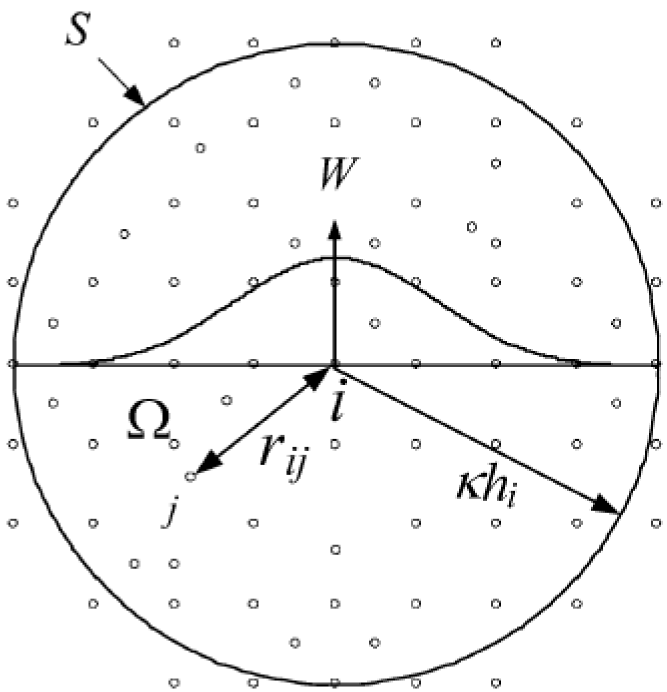
Both methods yield to 'vectorized' coding, making multiprocessor (parallel) computing easy

What is SPH?

- Numerical method for approximating probability densities over a domain of particles.
- Developed initially to model stars by Monaghan, et al, in 1977.
- Currently used mostly in hydrodynamic modeling and CG effects in film and video games.



How does SPH work?



Integral interpolant:

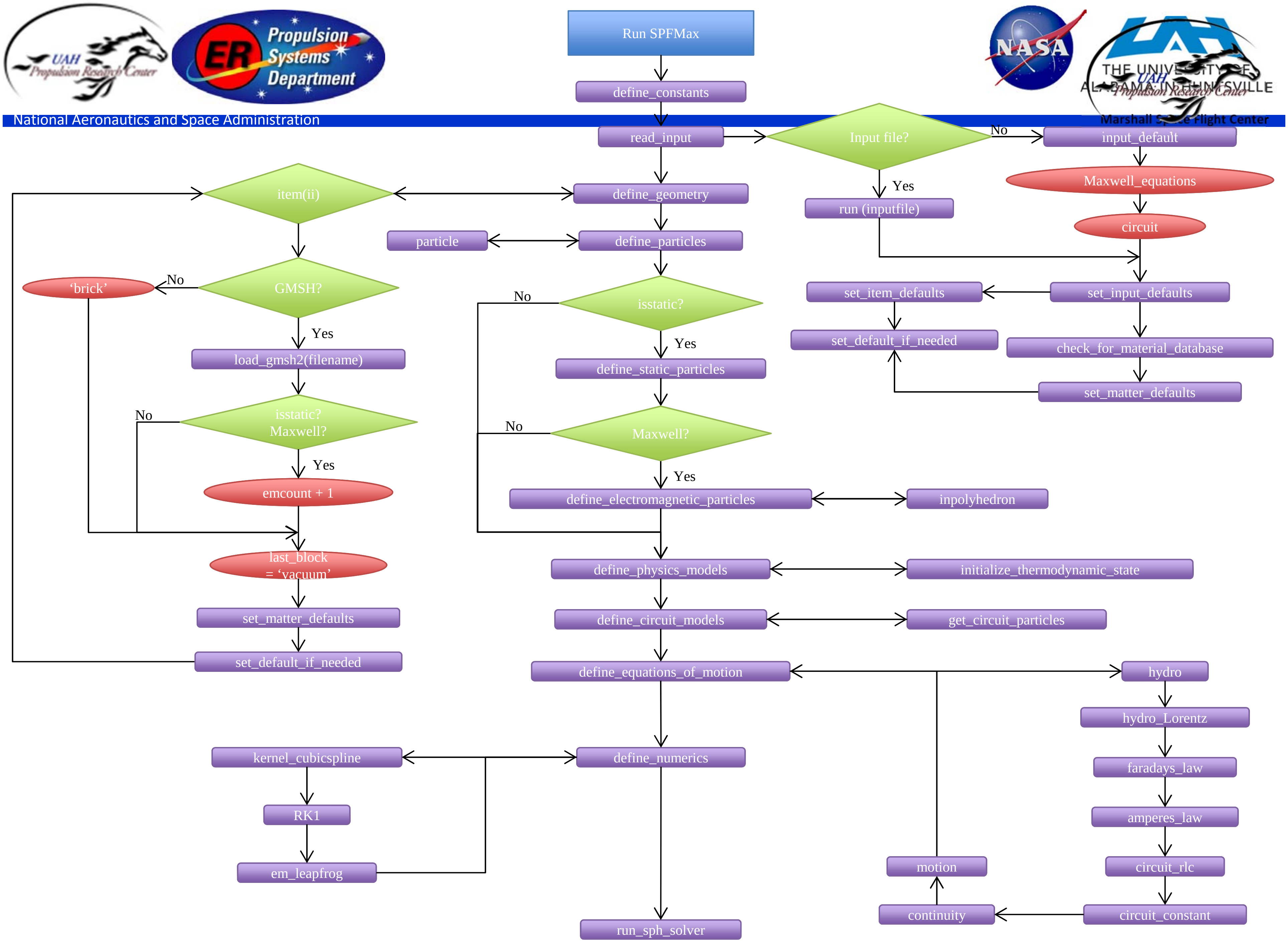
$$A_{\mathrm{I}}(r) = \int A(r')W(r - r', h)\mathrm{d}r'$$

A – quantity measured (density, temperature, etc.)
W – differentiable kernel function
d*r*‘ – volume differential
h – smoothing length.

Summation over mass elements:

$$A_{\mathrm{S}}(r) = \sum_b m_b \frac{A_b}{\rho_b} W(r - r_b, h)$$

Similar to density probability calculations.
How quantities are accurately calculated with a small particle domain.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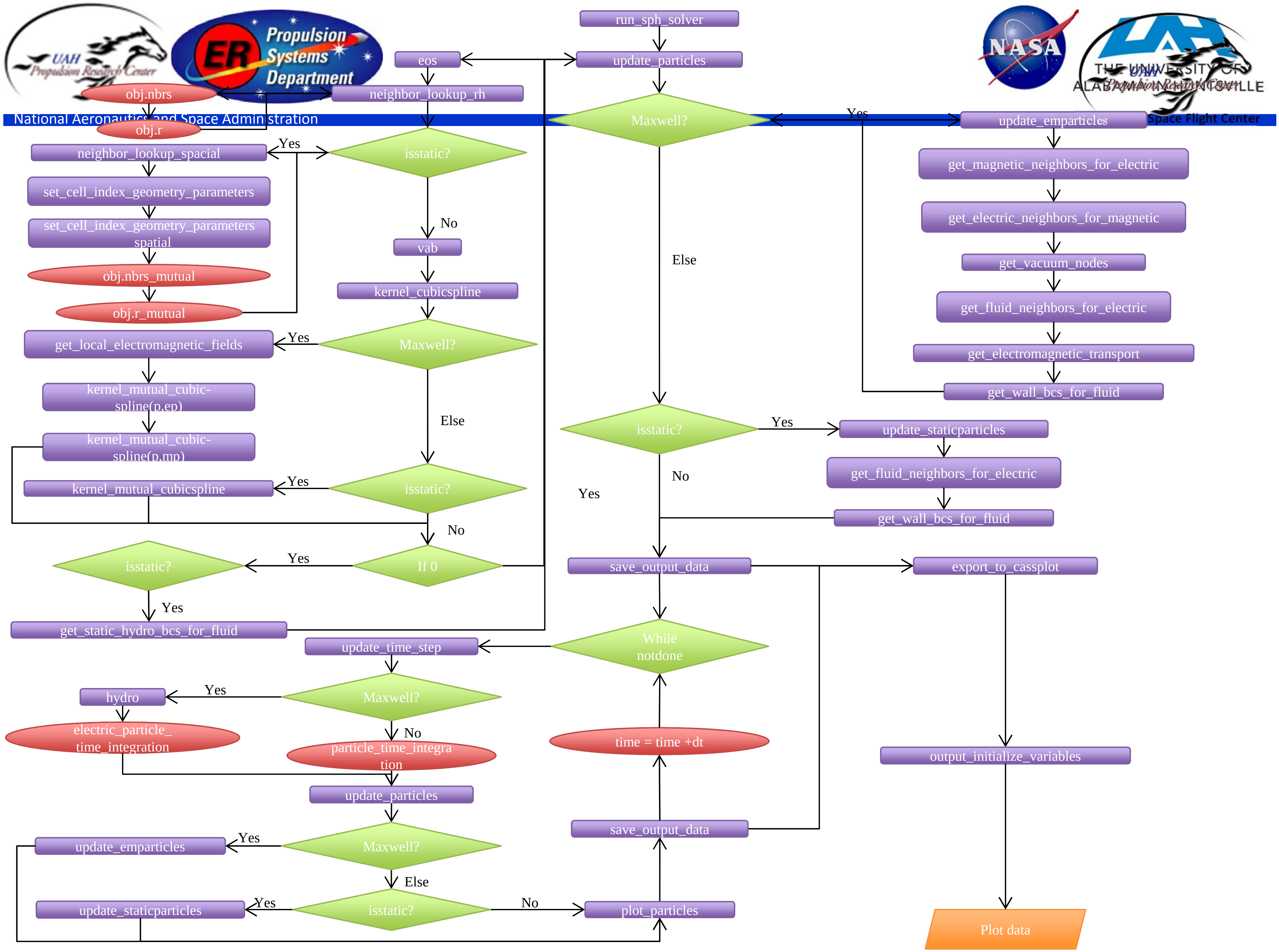
Run SPFMax
define_constants
read_input
Input file?
No
Yes
input_default
Maxwell_equations
circuit
run (inputfile)
set_input_defaults
set_item_defaults
set_default_if_needed
check_for_material_database
set_matter_defaults
define_geometry
item(ii)
particle
define_particles
GMSH?
'brick'
No
Yes
load_gmsh2(filename)
isstatic?
Maxwell?
emcount + 1
last_block
= 'vacuum'
set_matter_defaults
set_default_if_needed
isstatic?
define_static_particles
Maxwell?
define_electromagnetic_particles
inpolyhedron
define_physics_models
initialize_thermodynamic_state
define_circuit_models
get_circuit_particles
define_equations_of_motion
hydro
hydro_Lorentz
faradays_law
amperes_law
circuit_rlc
circuit_constant
continuity
motion
define_numerics
kernel_cubicspline
RK1
em_leapfrog
run_sph_solver



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National Aeronautics and Space Administration
NASA
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run_sph_solver
update_particles
eos
neighbor_lookup_rh
obj.nbrs
obj.r
neighbor_lookup_spacial
Yes
isstatic?
set_cell_index_geometry_parameters
set_cell_index_geometry_parameters spatial
obj.nbrs_mutual
obj.r_mutual
No
vab
kernel_cubicspline
get_local_electromagnetic_fields
Yes
Maxwell?
kernel_mutual_cubic-spline(p,ep)
kernel_mutual_cubic-spline(p,mp)
Else
kernel_mutual_cubicspline
Yes
isstatic?
No
isstatic?
Yes
If 0
Yes
get_static_hydro_bcs_for_fluid
Maxwell?
Yes
update_emparticles
get_magnetic_neighbors_for_electric
get_electric_neighbors_for_magnetic
get_vacuum_nodes
get_fluid_neighbors_for_electric
get_electromagnetic_transport
get_wall_bcs_for_fluid
Else
isstatic?
Yes
update_staticparticles
get_fluid_neighbors_for_electric
No
Yes
get_wall_bcs_for_fluid
save_output_data
export_to_cassplot
While notdone
update_time_step
Maxwell?
Yes
hydro
electric_particle_time_integration
No
particle_time_integration
time = time +dt
output_initialize_variables
update_particles
save_output_data
Maxwell?
Yes
update_emparticles
Else
isstatic?
Yes
update_staticparticles
No
plot_particles
Plot data

Equations of motion (completed)

$$\frac{\partial}{\partial t} n_e + \nabla \cdot \mathbf{u_e} = 0$$

$$\frac{\partial}{\partial t} n_i + \nabla \cdot \mathbf{u_i} = 0$$

$$n_e m_e \frac{\partial}{\partial t} \mathbf{u_e} + \nabla p_e + e\, n_e \left(\mathbf{E} + \mathbf{u_e} \times \mathbf{B} \right) = -$$

$$n_i m_i \frac{\partial}{\partial t} \mathbf{u_i} + \nabla p_i - Z\, e\, n_i \left(\mathbf{E} + \mathbf{u_i} \times \mathbf{B} \right) =$$

$$\frac{3}{2} n_e \frac{\partial}{\partial t} k T_e + p_e \nabla \cdot \mathbf{u_e} = -\pi_e : \nabla \mathbf{u_e} - \nabla \mathbf{h_e} - \left(\mathbf{u_e} - \mathbf{u_i} \right) \cdot \mathbf{R_e} - Q_i$$

$$\frac{3}{2} n_i \frac{\partial}{\partial t} k T_i + p_i \nabla \cdot \mathbf{u_i} = -\pi_i : \nabla \mathbf{u_i} - \nabla \mathbf{h_i} - Q_i$$

Transport effects, which can be based on nonequilibrium distribution functions (kappa and power law)

$$\mathbf{R}_\alpha \equiv \int m_\alpha \mathbf{w} \sum_\beta C_{\alpha\beta}\, d\,\mathbf{w}$$

$$\mathbf{R}_\alpha \approx -\sum_\beta m_\alpha n_\alpha \left(\mathbf{V}_\alpha - \mathbf{V}_\beta \right) \langle \nu_{\alpha\beta} \rangle$$

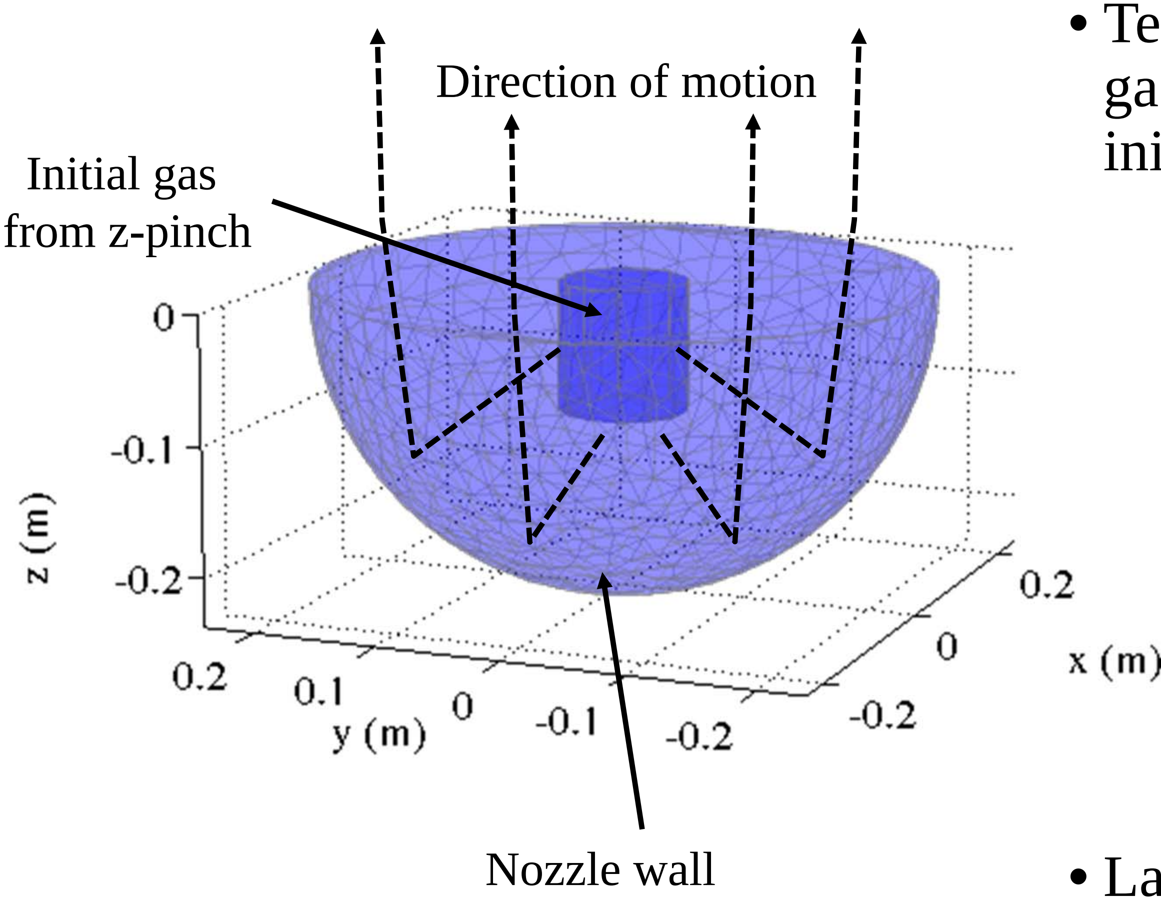
$$p_\alpha \equiv \frac{1}{3} n_\alpha m_\alpha \langle w^2 \rangle$$

$$\pi_i \equiv n_\alpha m_\alpha \langle \mathbf{w}\mathbf{w} \rangle - p_\alpha \mathbf{I}$$

$$h_\alpha \equiv \frac{1}{2} n_\alpha m_\alpha \langle w^2 \mathbf{w} \rangle$$

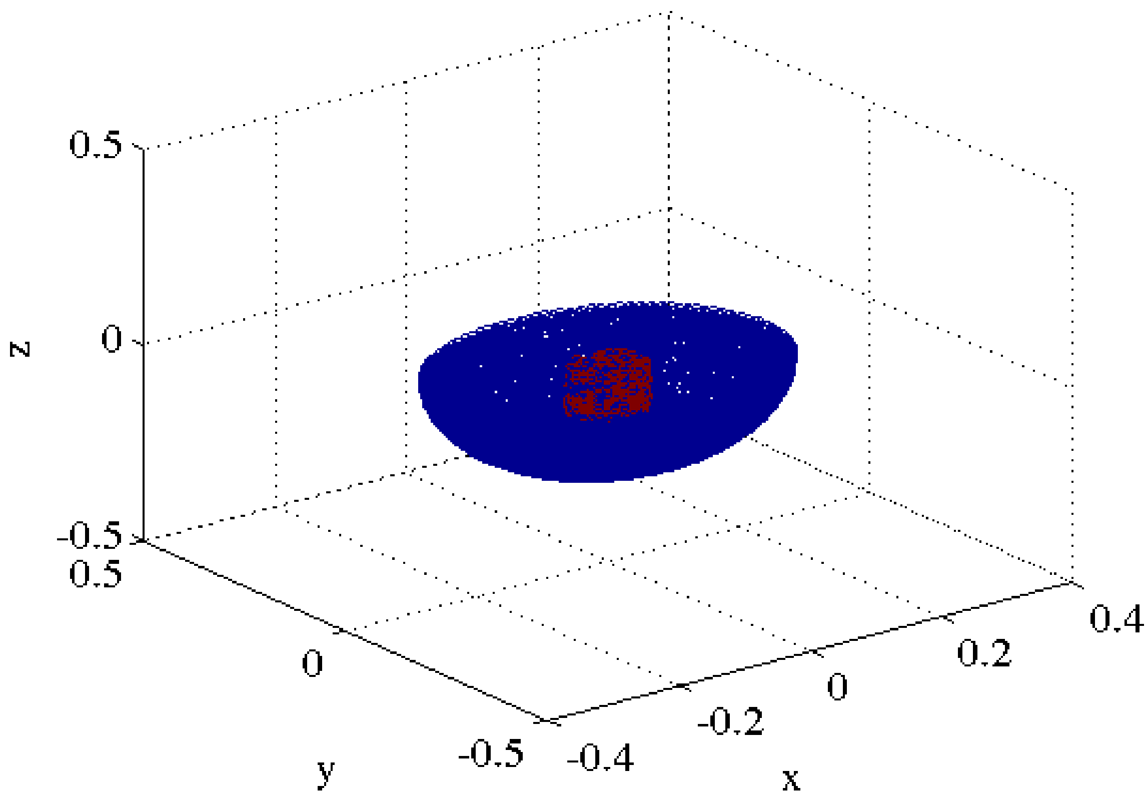
$$Q_\alpha \equiv \int \frac{1}{2} m_\alpha w_\alpha^2 \sum_\beta C_{\alpha\beta}\, d\,\mathbf{w}$$

Initial Pulsed Nozzle Model



- Test thermal expansion of gas nozzle with various initial conditions
  - Nozzle geometry
  - Gas
    - Temperature
    - Density
    - Radius
    - Length
    - Composition
- Lays ground work and expectations for magnetic nozzle

Preliminary results



Preliminary results

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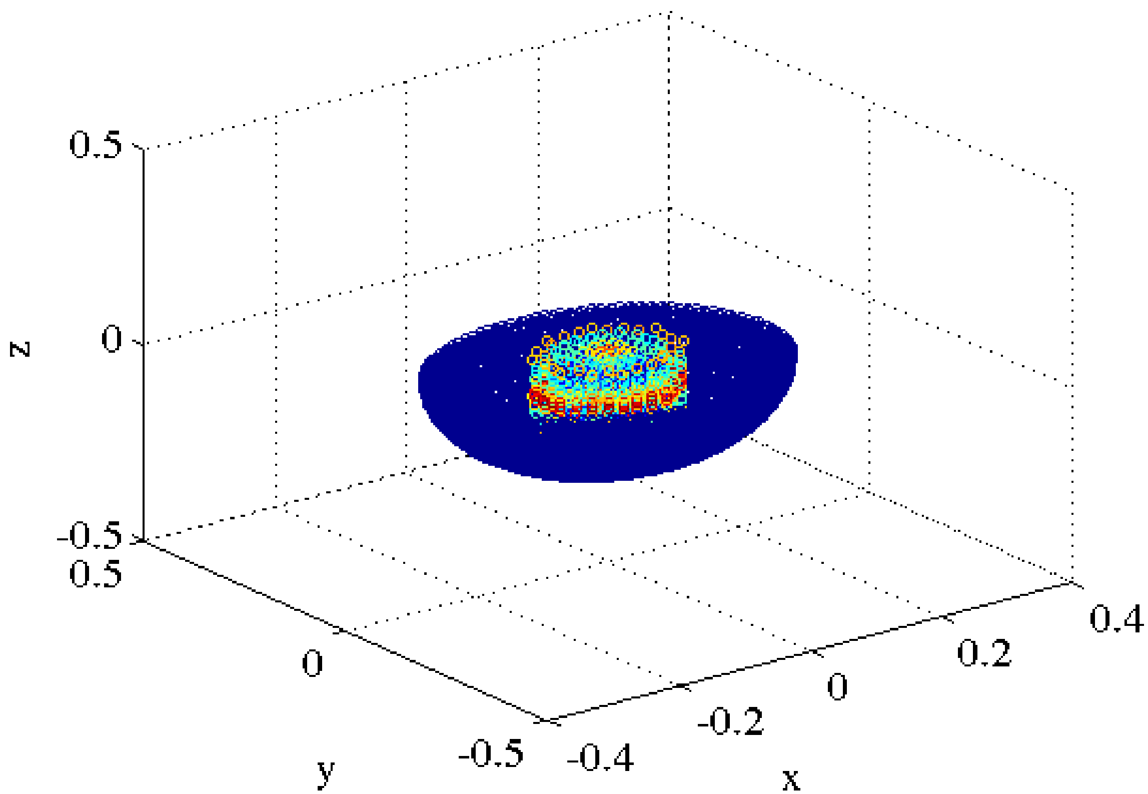
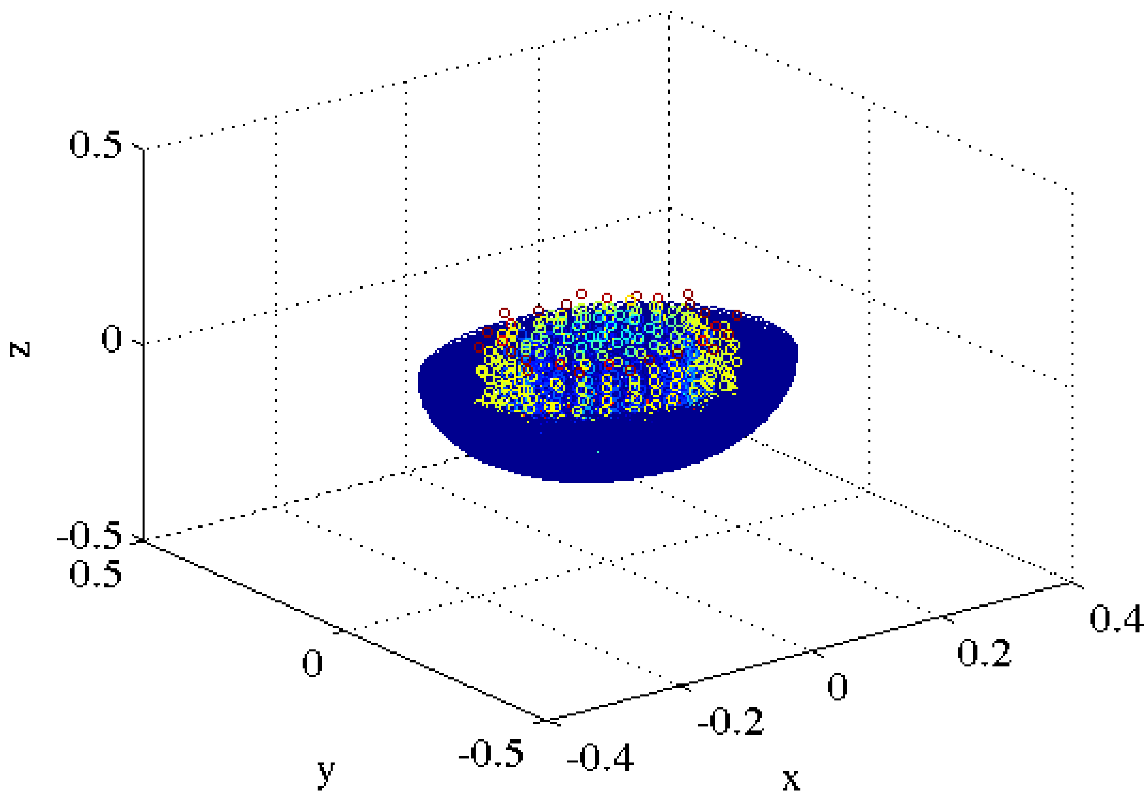
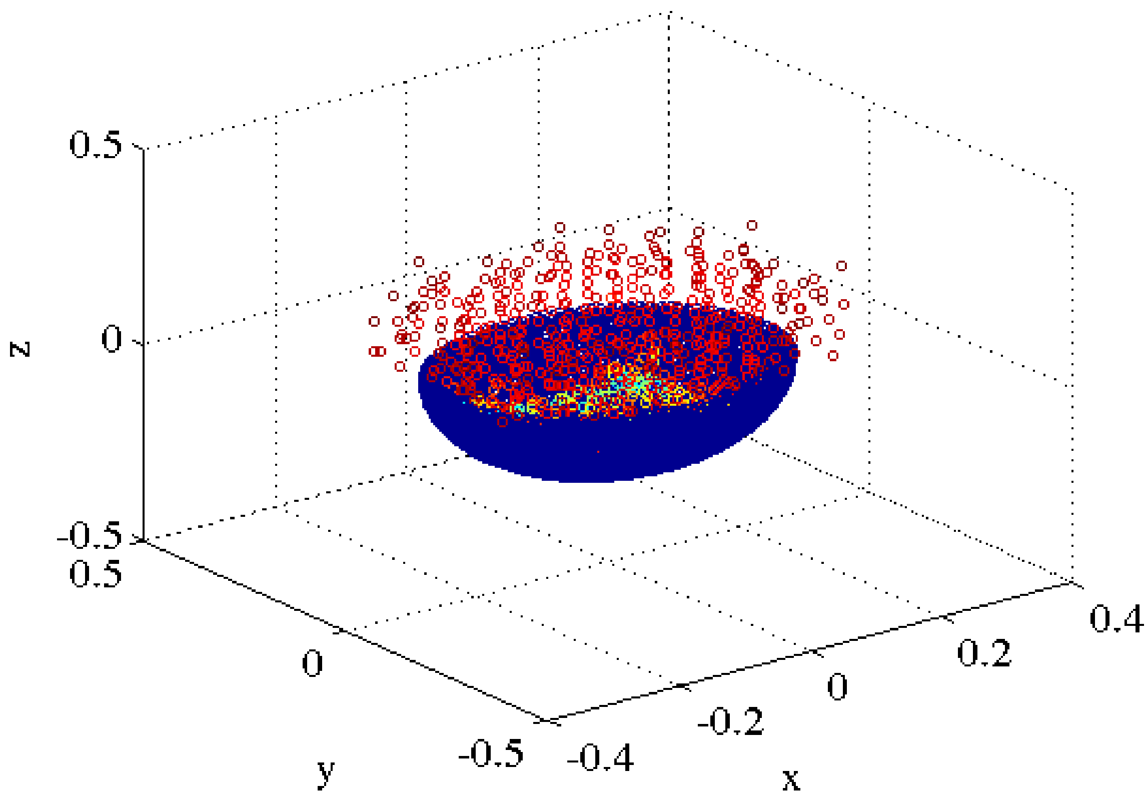


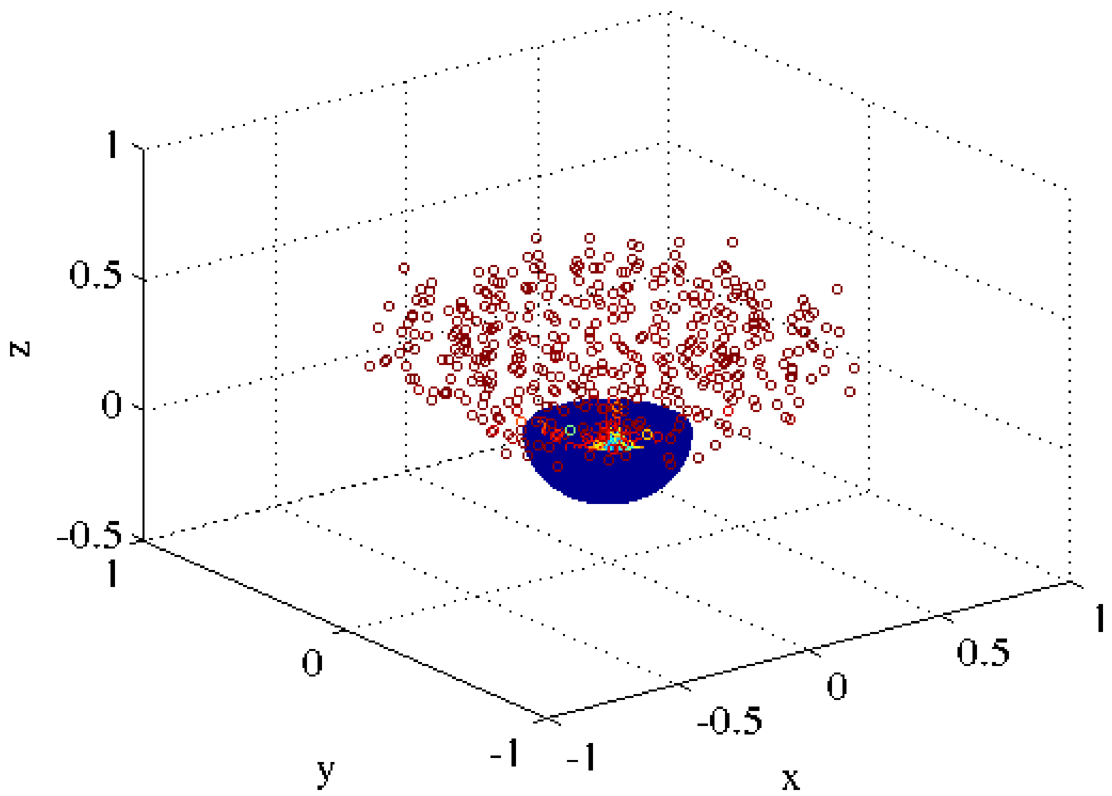
Preliminary results



Preliminary results

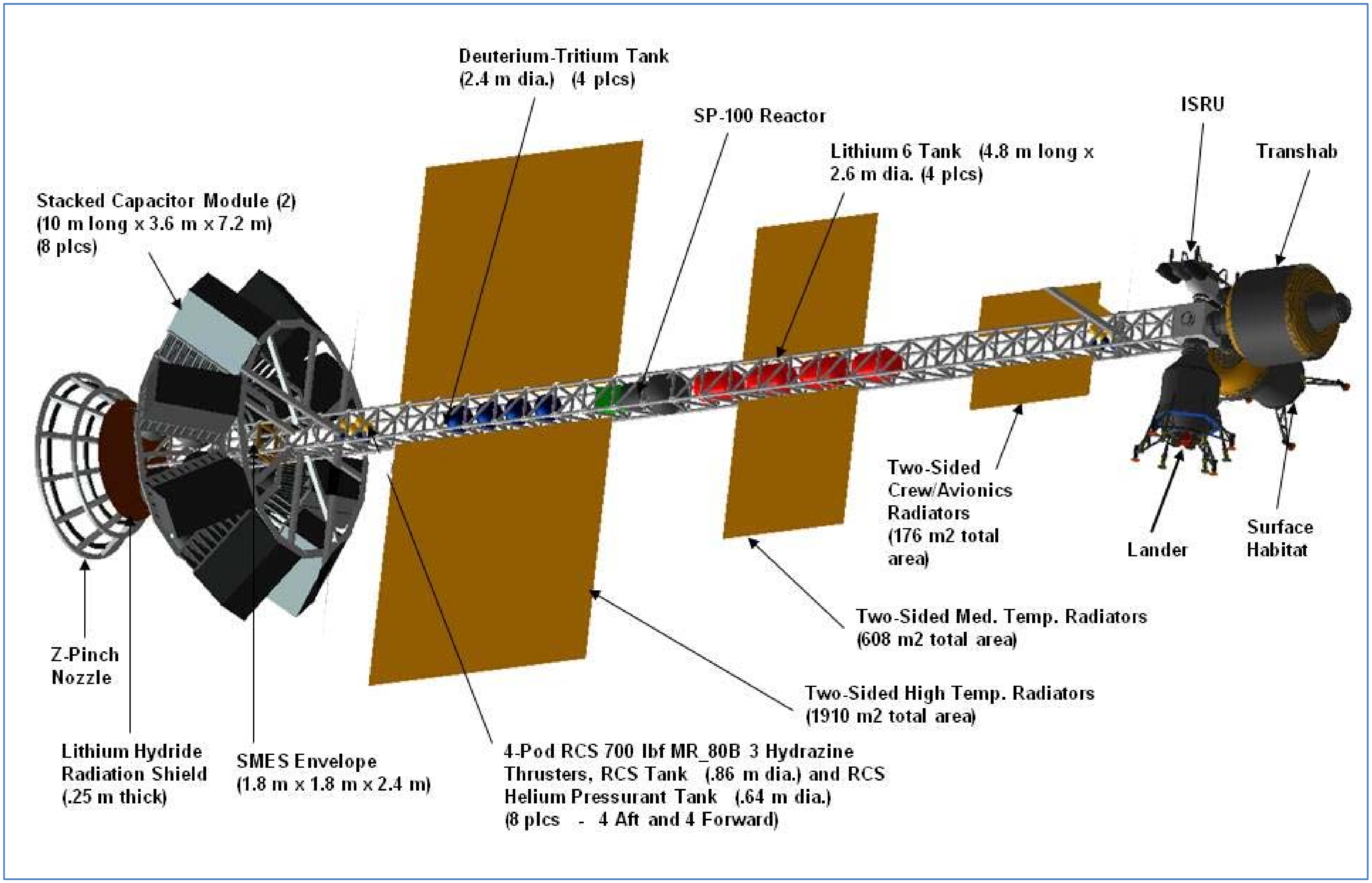


Preliminary results



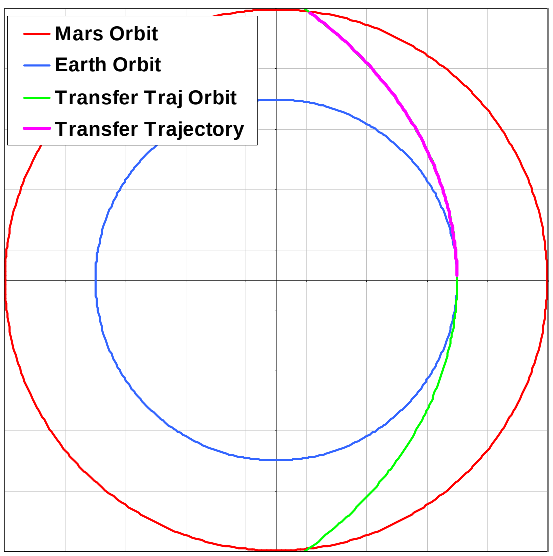
NIAC Phase I Goals

Crewed Mars Mission Concept



Mission Concepts

	Mars 90	Mars 30	Jupiter	550 AU
Outbound Trip Time (days)	90.2	39.5	456.8	12936
Return Trip Time (days)	87.4	33.1	521.8	n/a
Total Burn Time (days)	5.0	20.2	6.7	11.2
Propellant Burned (mT)	86.3	350.4	115.7	194.4
Equivalent DV (km/s)	27.5	93.2	36.1	57.2



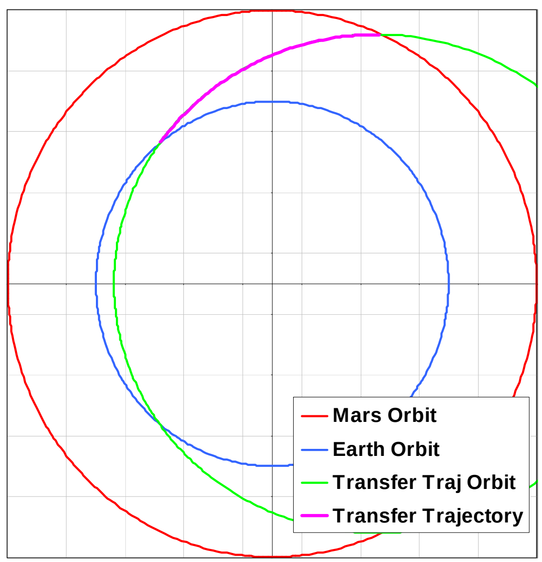


Figure 3 Mars 90 Day Transfer Trajectories

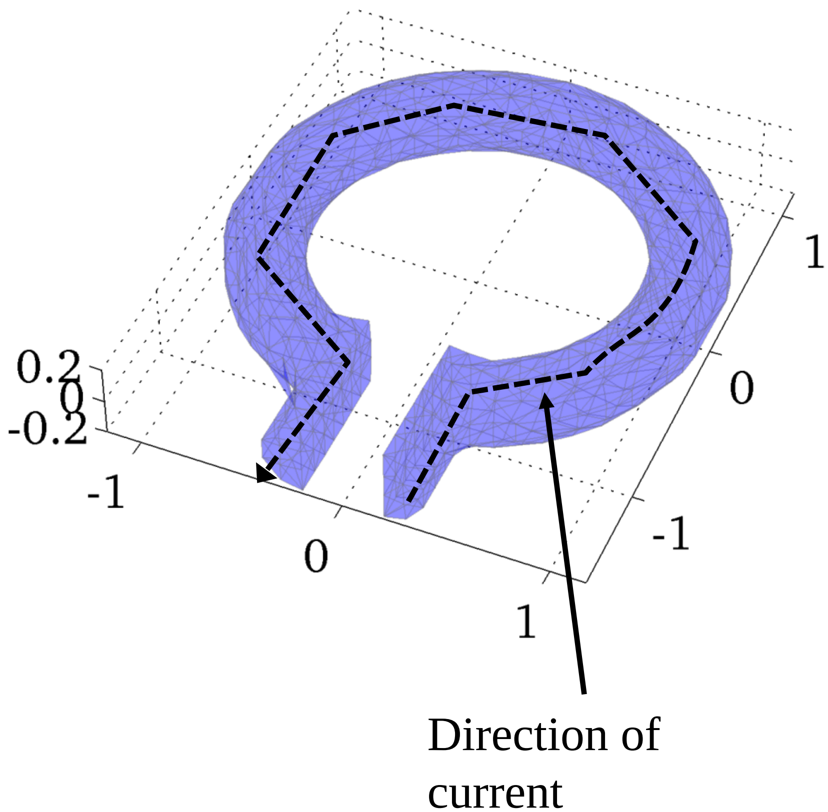
- **Engine**
  - Isp = 19,400 sec
  - T = 38 kN
  - 10 Hz pulse freq.
- **Vehicle**
  - M_{dry} = 552 mT
  - M_{pay} = 150 mT
  - 30% MGA

Polsgrove, T. et al. Design of Z-Pinch and Dense Plasma Focus Powered Vehicles, 2010 AIAA Aerospace Sciences Meeting

Mating SPFMaX and MCNP

- **SPFMax gives**
  - Ability to model 3d effects
  - Can propagate magnetic fields in vacuum
  - Easily editable
- **MCNP**
  - Track neutron life, fission reactions
  - Flexible geometries
- **Second half of NIAC is to run codes concurrently**
  - synchronize neutron population vs. time
  - Optimize energy output
    - As function of geometry
    - As function of composition
      - Mix of UF6, D-T
      - Lithium liner thicknesses

Single turn Magnetic Nozzle



- Gasdynamic nozzle performance to be compared with magnetic nozzle to assess loss mechanisms in magnetic nozzles, e.g.
    - Field/plasma instabilities
    - Plasma detachment

NIAC Phase II Experimental Options

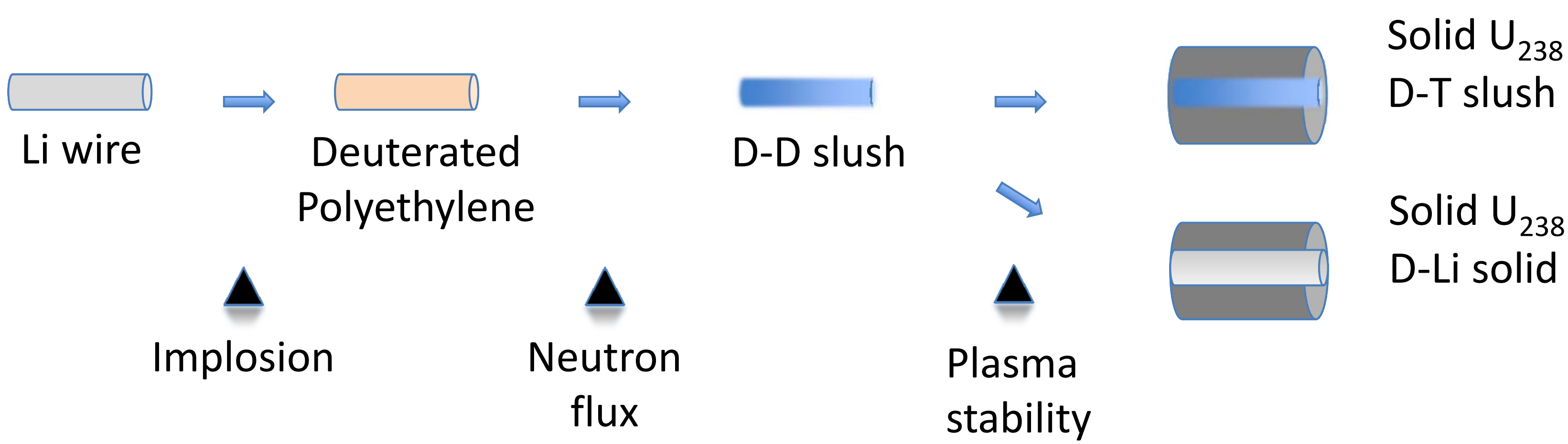
Charger - 1

- A test facility for high power and thermonuclear fusion propulsion concepts, astrophysics modeling, radiation physics
- Located in the UAH Aerophysics Lab at Redstone
- The highest instantaneous pulsed power facility in academia – 572 kJ (1 TW at 100 ns)

Experimental Roadpath

Methodology

- Incremental improvements in experimental capability
- Benchmark model with experimental data
- Can also run any experiments below with lower power systems
- Looking for comments and suggestions here!



Long Range Plans

- **Charger II**
  - Construct breadboard PuFF system capable of 10-20 Hz operation
    - Upgrade to flight weight hardware – NASA
    - Optimize pulse for maximum power output – DOE
    - Astrodynamics, radiation protection, other research goals - Various